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THE INFLUENCE OF POLYMER-SECRETING ORGANISMS ON FLUID FRICTION AND CAVITATION

by

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ABSTRACT. Substances produced by organisms living and growing in water are of special interest to naval architects, since their presence may greatly change frictional resistance determinations made in the towing tank and at sea. To indicate the possible changes in resistance that might be encountered, experiments with fresh-water and marine plankton cultures, as well as with larger algae, are described. In these experiments, friction reductions of as much as 65% were recorded.

The influence of these high-polymer substances on cavitation inception, appearance, and damage is now under active study. Preliminary findings regarding their effects are presented. Methods of detecting the presence of algae-produced compounds are also discussed, together with their possible effects on towing-tank, water-tunnel, and at-sea testing techniques.

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INTRODUCTION

For many years, naval architects have regarded the ocean traversed by their ships as an inanimate substance with well-defined, reproducible, and constant properties, such as density and viscosity, that can be predicted in advance. Similar concepts were held regarding the water contained in towing tanks and water tunnels.

To the student of the marine environment, however, the ocean is a "living broth" in which the total amount of photosynthesis equals that which takes place on land, and in which the production or protein through the food chain is continuous and on a scale so enormous as to be almost unimaginable.

The assumption that the great life processes of the ocean have no influence on manmade ships other than, perhaps, the biological fouling of hulls has generally been a valid one. Nevertheless, there have been some puzzling anomalies. On occasion, the trials of supposedly identical sister ships, tested some months apart, have been characterized by fairly wide variations in the power required for a given speed--variations greater than could reasonably be expected from shipyard tolerance deviations.

On a smaller scale, the resistance of ship models measured in towing tanks sometimes seems to vary, with no explanation other than a so-called "change in the resistance quality of the water." There have even been occasional periods in some towing tanks when resistance "storms" occurred and the apparent friction was greatly decreased for a length of time extending to months.

The recent discovery that dilute high-molecular-weight polymer solutions may have unusually low turbulent-flow friction coefficients has provided a key to understanding these anomalies. It now appears that many marine organisms are capable of secreting high-polymer substances into the sea (or into a towing tank, in the case of fresh-water organisms) that are effective in changing the turbulent-friction resistance of immersed bodies. The presence of these naturally produced materials can greatly change frictional-resistance determinations made in the towing tank and at sea.

Further, it is reasonable to suspect that these substances, which affect friction so markedly, may also play a role in altering cavitation inception, appearance, and erosion.

FRICTION REDUCTION OF MICROSCOPIC ALGAE

By causing cultures of living phytoplankton to flow through a small pipe at a given rate, and by comparing the pressure drop in a known length with that obtained under the same conditions with water, evidence of frictional change attributable to the influence of the algae can readily be shown.

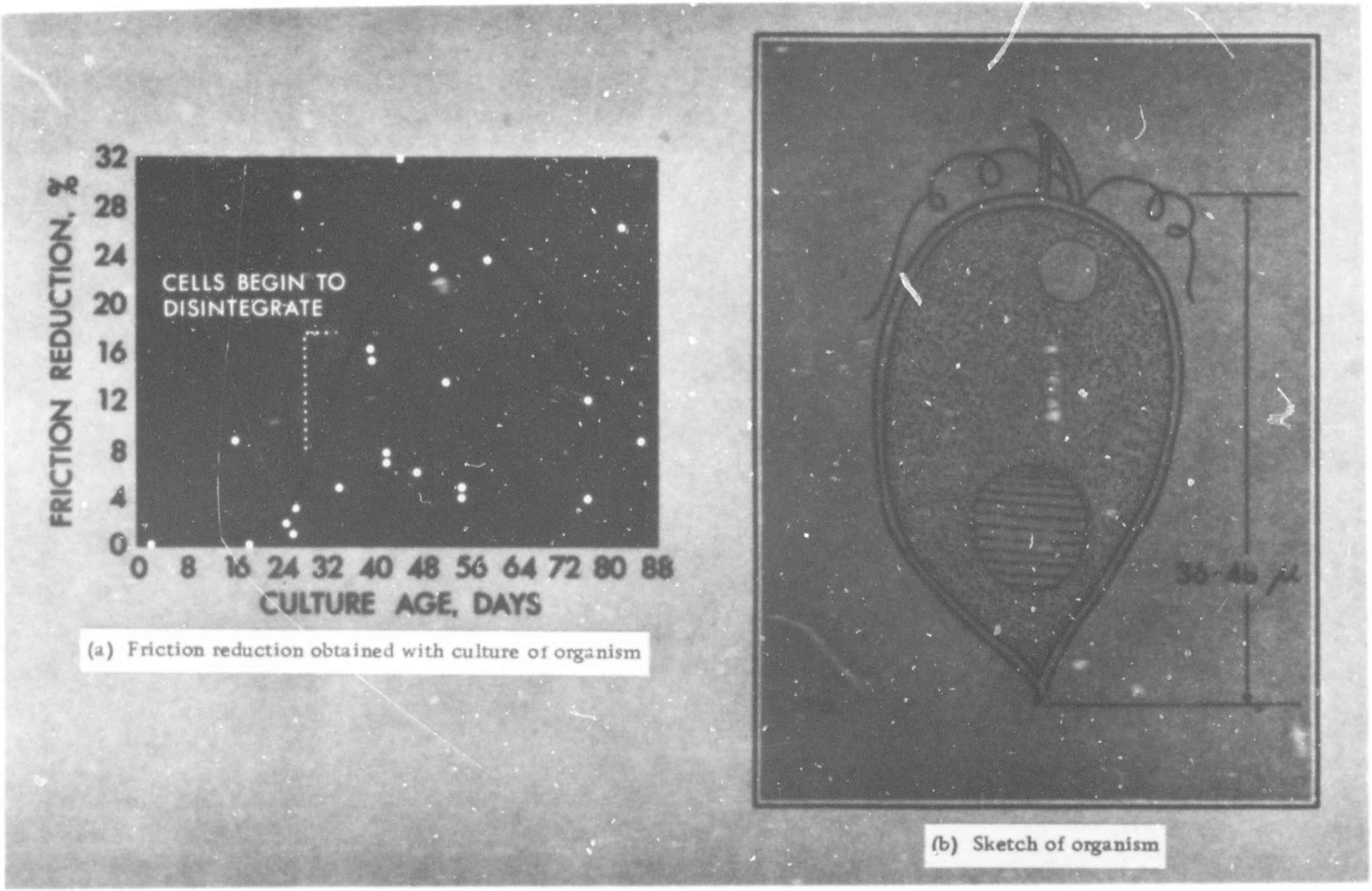
In this way, cultures representing all of the main classes of microscopic algae have been found to exude substances that reduce friction. In briefest terminology, the algae may be divided into groups generally separable by color:

1. Blue-green
2. Green
3. Red
4. Brown
5. Yellow-brown

Microscopic or single-cell marine forms may be found in all of these groups; in the ocean, however, the most prominent are the yellow-brown diatoms. Also important is another large category not identifiable by color, the dinoflagellates or unicellular swimming forms.

Several representatives of each of these great classes of marine organisms have demonstrated the capability of secreting high-polymer substances in laboratory cultures. Many dinoflagellates, and some other types, are equipped with special pores or ducts for secreting the material (described in detail in Ref. 1). Exactly why this is done is not known; presumably, there is a protective or possibly antibacterial action in the materials. However, the naval architect's main interest lies in the fact that the substances often are soluble, high-weight, and apparently linear molecules that, in sufficient concentration, will reduce friction.

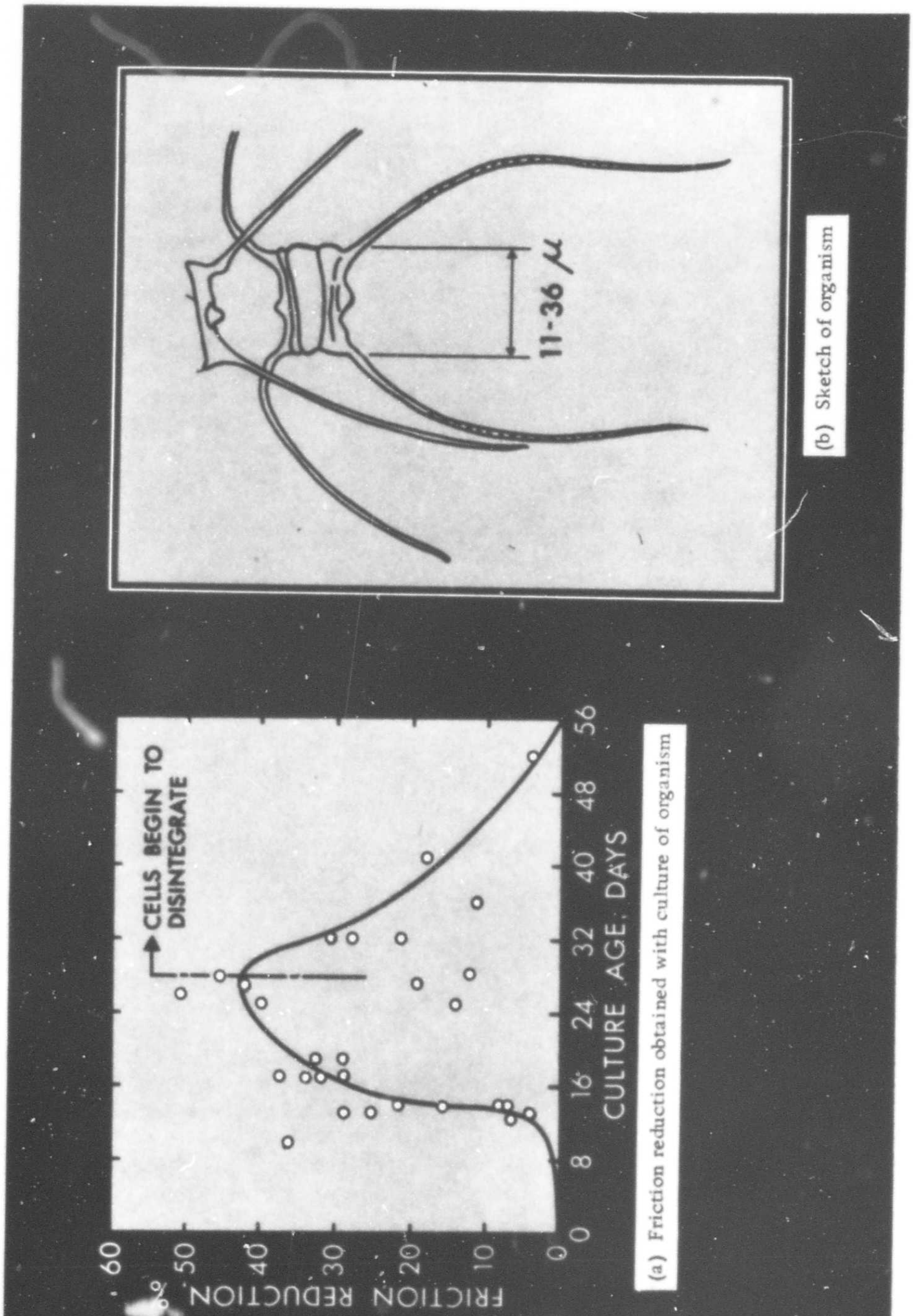
As an example of the dinoflagellates, the very common Prorocentrum micans, found in both Atlantic and Pacific waters, is an excellent friction reducer in laboratory culture, as shown in Fig. 1a-b. The friction-reducing substances of this species are liberated toward the end of the active growth period. With the diatom Chaetoceros didymus (Fig. 2a-b), liberation of the friction-reducing substances accompanies the period of rapid growth. With both organisms, substantial friction reductions (i. e., of more than 25%) are readily obtained. These data were taken at pipe-flow Reynolds numbers (based on pure water) of 10,000 to 14,000. The cells of the algae play no part in the effect; removing the cells by centrifuging does not change the observed friction reduction. Although there is inconsistency in the data shown in Fig. 1 and 2, the general trend of the friction reduction with time was established by following the progress of individual cultures, and this trend is represented by the curves. The scatter in these data is due



(a) Friction reduction obtained with culture of organism

(b) Sketch of organism

FIG. 1. The Dinoflagellate Prorocentrum micans.



(a) Friction reduction obtained with culture of organism

(b) Sketch of organism

FIG. 2. The Diatom *Chaetoceros didymus*.

to differences in the general physiological state of the organisms. Large variations in growth rate and the amount of polymer secretion were observed in early tests before optimum growth conditions were obtained in the laboratory. All data obtained during the course of the study are presented in the curves; the important concept is that the cultures produce definite friction-reducing effects. No attempt is therefore made to fix on a given value.

All algae were cultured in completely defined synthetic media that had been proven to have the same frictional characteristics as distilled water. Some species were bacteria-free; in others, the bacteria contaminates were cultured separately and checked for friction reduction. In every case examined, the friction reduction was attributable to the algal cells and not the bacteria.

While some algae secretions decay in friction-reducing effectiveness relatively quickly, others resist breakdown by bacteria and retain full friction-reducing ability for long periods of time. Initially, the resistance-changing substance concentration parallels cell growth, as shown in Fig. 3 for a marine Porphyridium species. After cell division ceases, however, the substance retains its effectiveness for a year or more in laboratory cultures.

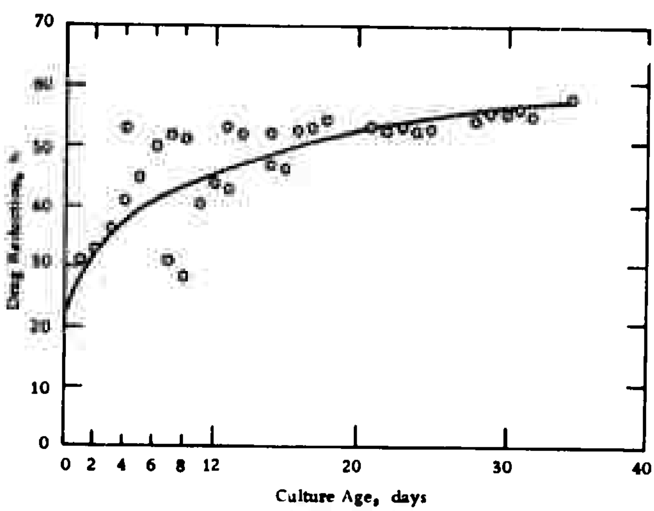


FIG. 3. Friction Reduction Obtained With Cultures of a Porphyridium Species.

Since various species of diatoms, dinoflagellates, and other algae occur in dense "blooms" in the surface water of the ocean from time to time (usually in the spring but occasionally at almost any season), it seems possible that ships could be operated in an ocean area containing sufficient high-polymer exudate to lower the skin-friction coefficient. If this were to occur on a trial run of a new ship, the instrumentation aboard would indicate a pleasing result to the naval architect; the propulsive power necessary to maintain a certain speed would be lower than predicted.

In bodies of fresh water, there are also many microscopic algae that exude high-polymer substances and could cause changes in frictional resistance if they were present in a towing tank or water tunnel. (The possibility that resistance changes might occur in a towing tank by any means was first advanced in Ref. 2.) In experiments with fresh-water algae, the following results were obtained.

Algae	Drag Reduction, %
Anabaena floss-aquae (blue-green)	59.5
Chlamydomonas peterfii (green)	29.0
Porphyridium aerugineum (red)	65.0

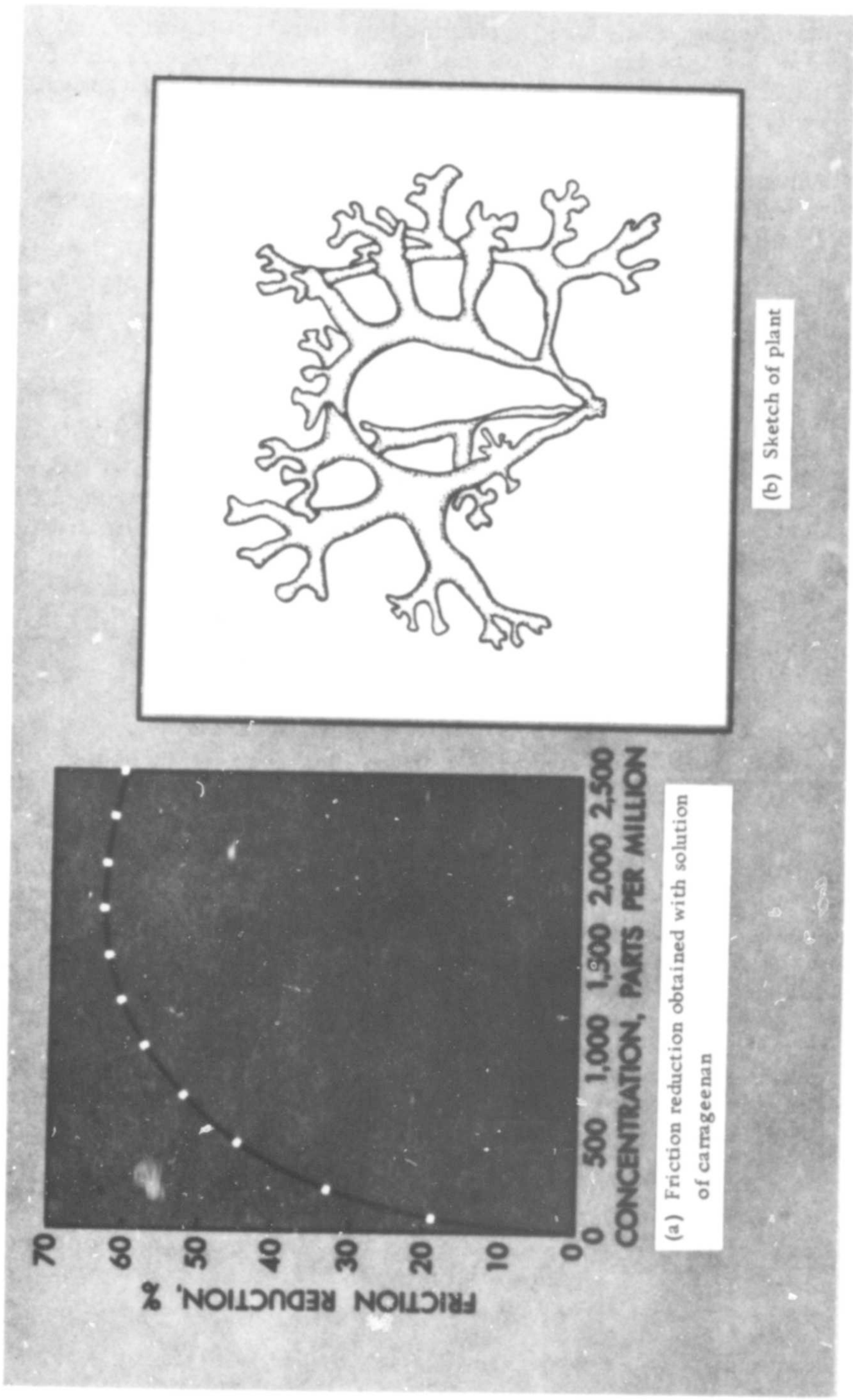
These drag reductions clearly indicate that algae should be carefully excluded from towing tanks. The Anabaena listed above was one of the organisms identified in the towing tank at Ft. Steyne, Isle of Wight, England, in which drag measurements were seriously affected by substances of biological origin (Ref. 3).

Recent experiments with synthetic high polymers deliberately dissolved in towing-tank water leave little doubt that the drag may be greatly reduced by this means (Ref. 4); as few as 1.5 parts per million (ppm) by weight of the synthetic polymer poly(ethylene oxide) reduced the drag of a flat plate by almost 40% in the towing tank of the Aerojet-General Corp., Azusa, Calif. (Ref. 5).

FRICTION-REDUCTION QUALITIES OF LARGER ALGAE

Many of the larger algae, or seaweeds, are harvested commercially for the extraction of their water-soluble materials, which are used as thickeners and viscosity builders in food and industrial applications. These thickening agents also have friction-reducing qualities in dilute solution. Figure 4a-b shows test results with carrageenan, the commercial extractive of Chondrus chrispus, a common red seaweed.

During 1966, approximately 65 species of fresh seaweed were tested, most of them from the west coast of the United States but some



(a) Friction reduction obtained with solution of carrageenan

(b) Sketch of plant

FIG. 4. Chondrus chrispus and its **Derivative**, Carrageenan.

from Japan and the Mediterranean. Of these, 50 yielded a friction-reducing solution when extracted with hot sea- or fresh water. The liberation of organic materials into the sea by large algae is the current topic of much research; clearly, there is a possibility that the larger sea plants can affect the resistance characteristics of the surrounding water. This phenomenon is most frequently manifested by the changed appearance of the water surface in the region of large "kelp" beds offshore. Figure 5 shows the friction reduction obtained from a sample of a common large algae.

The concern of those who are connected with the sea trials of ships must be to avoid making measurements in areas containing large growths of seaweed.

CAVITATION INCEPTION

In 1965, Lt. R. J. Prather, U. S. N., assigned to the U. S. Naval Ordnance Test Station, observed that the inception point of a cavitating fluid jet was considerably retarded when the high-polymer substances poly(ethylene oxide) and guar gum were added to the test solution. In particular, he found that the cavitation index, sigma, which was defined as

$$\sigma = \frac{P_{\text{throat}}}{\frac{1}{2}\rho v^2}$$

was reduced from 0.49 for a water jet to approximately 0.3 for a 50-ppm poly(ethylene oxide) solution, and 0.3 also for a 500-ppm guar gum solution.

Early in 1967, A. T. Ellis of the California Institute of Technology studied cavitation inception on a hemisphere-nosed cylindrical body in a blow-down water tunnel (Ref. 6). Using a stainless-steel test body 0.65 centimeter in diameter, cavitation inception was detected in two ways. A laser beam was adjusted to barely graze the surface of the hemisphere nose in the region where cavitation first appears. Light scattered by the cavitation bubbles was detected by a photocell sensing the light at about 90 degrees from the laser beam direction (Fig. 6). This method of cavitation detection was checked by acoustic observation, and extremely close agreement was obtained.

Tests were made with water (passed through a 0.4-micron filter) at 20, 50, and 100 ppm poly(ethylene oxide), and with a suspension of Porphyridium aerugineum. The test fluid for the algae case consisted of 15.31 liters of culture, which produced a friction reduction of 29.3%, diluted with a further 565 liters of water.

All tests in this series were made with water containing about 17 ppm dissolved air, as measured with a Van Slyke apparatus.

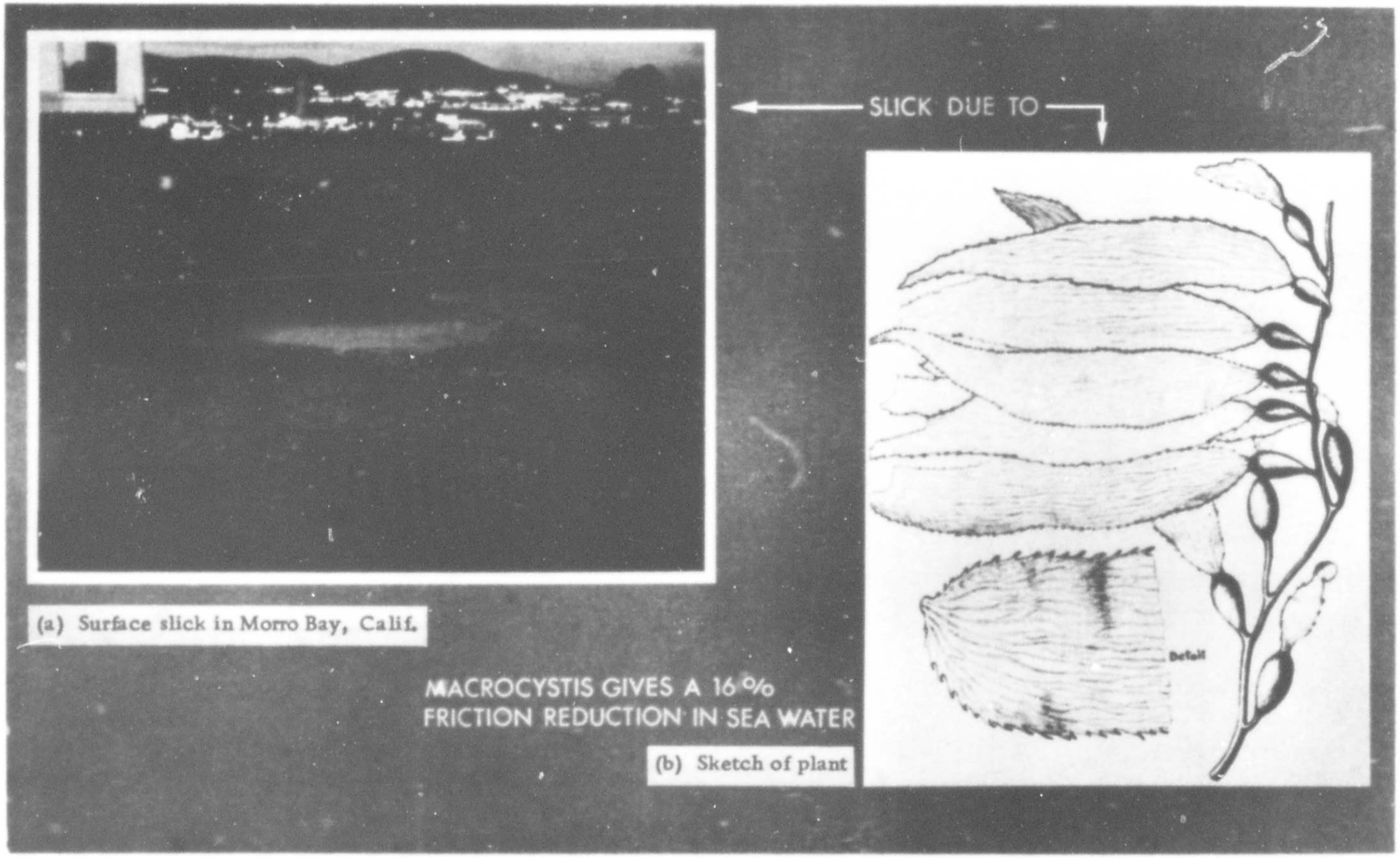


FIG. 5. Macrocystis and its Effect on the Sea Surface.

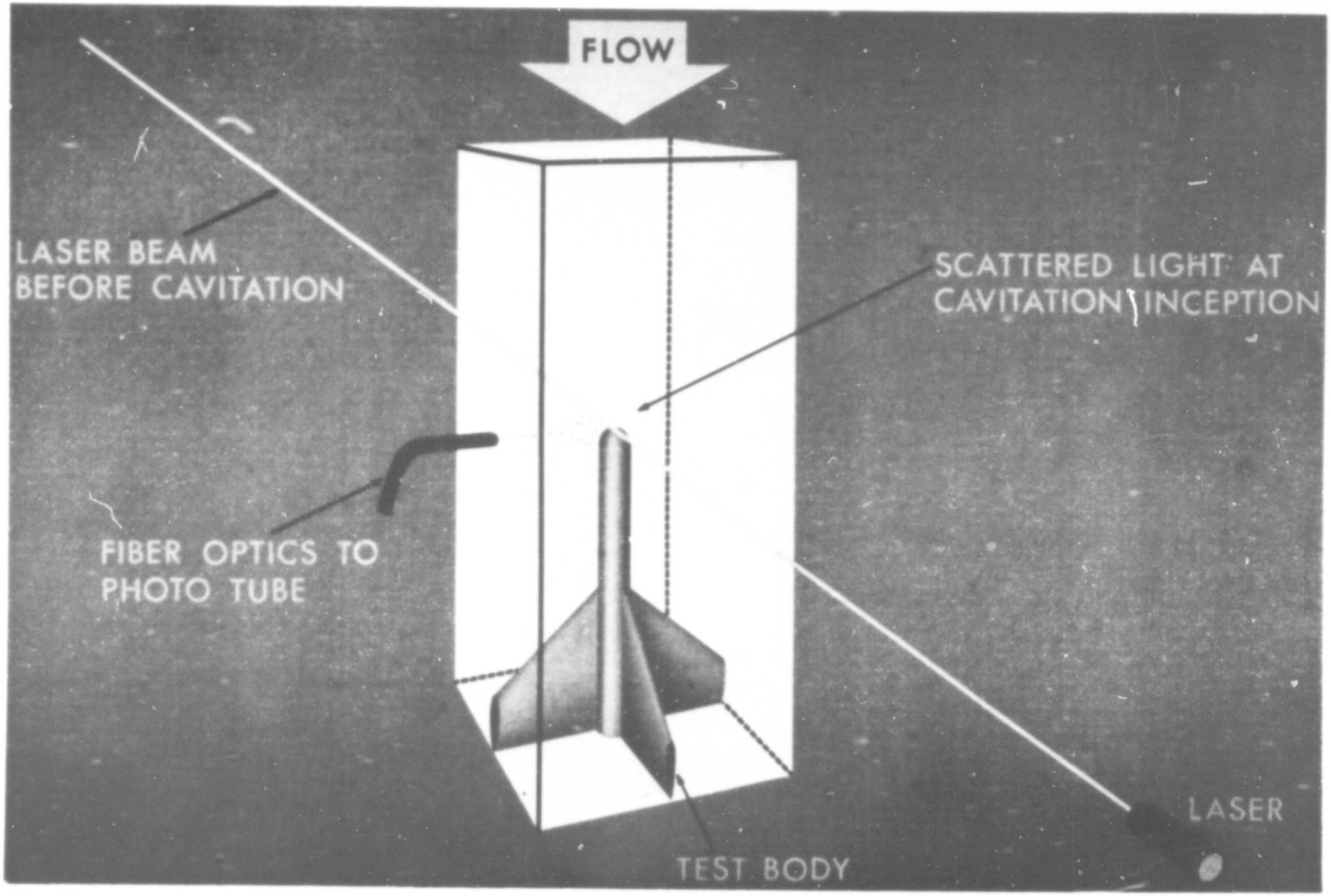


FIG. 6. Cavitation Inception Monitoring Equipment.

Typically, the polymer solutions have a reduced surface tension; measurements of a 50-ppm poly(ethylene oxide) solution indicate a surface tension of 62.2 dynes/cm; 100 ppm yielded a value of 61.4 dynes/cm.

The following inception data were obtained (averaged over four runs).

	Tunnel Velocity, m/sec	Cavitation Inception Index
Water	12.55	0.73
20 ppm Polyox	13.40	0.50
50 ppm Polyox	14.18	0.39
100 ppm Polyox	13.70	0.41
Algae	12.88	0.66

Thus it can be seen that the polymer content of the water has a marked effect on the cavitation inception point. This may be a factor in explaining the large differences in inception index in tests of the same body shape in water tunnels throughout the world (Ref. 7).

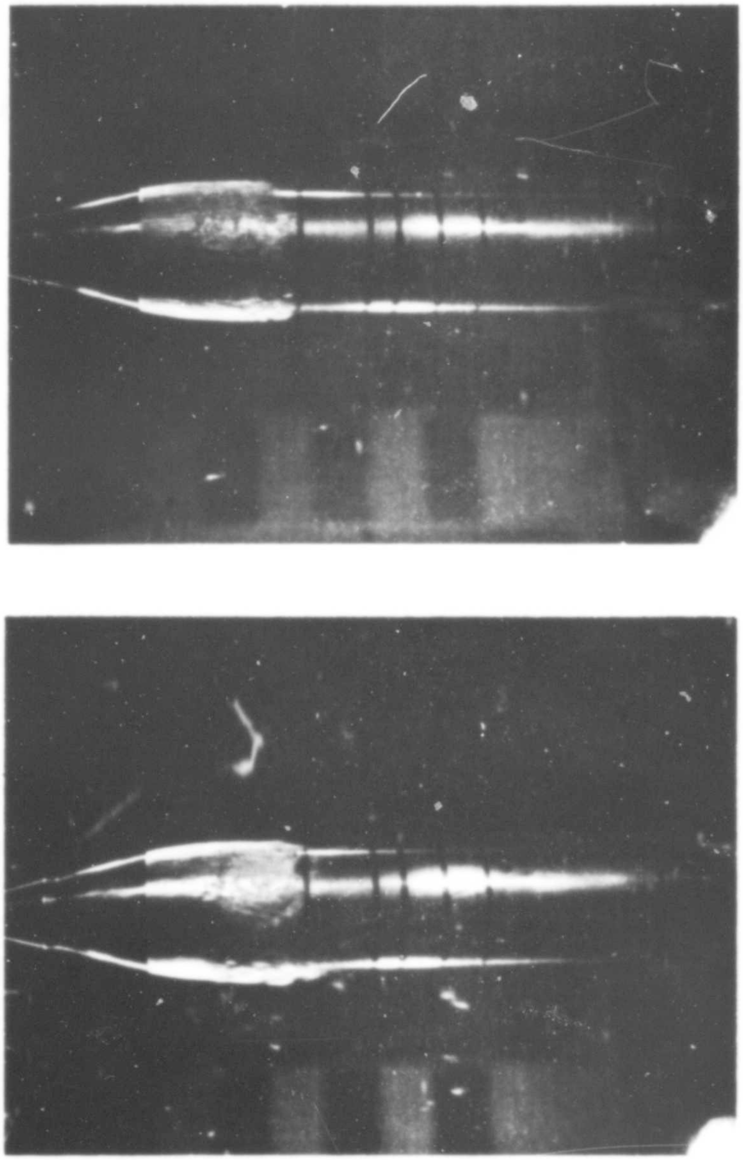
OBSERVATIONS OF CAVITATION APPEARANCE

There is a noticeable difference in the appearance of steady-state cavities in flows containing high-polymer substances in solution, as compared with observations at the same cavitation index in pure water. Figure 7 shows the comparison for a tripped cavity on a body of revolution between water and a 50-ppm poly(ethylene oxide) solution, both at a cavitation index of 0.22. The polymer solution cavity is more striated, and appears to collapse less violently than the water cavity; high-frequency response-pressure measurements confirm the diminution of the fluctuation intensity (Ref. 8).

The initial appearance of the cavitation bubble is also changed by the presence of a high-polymer substance. In the experiments at the California Institute of Technology mentioned earlier, cavitation inception over the hemisphere-nosed cylindrical body was detected by the scattering of a laser beam. A photocell was used to detect the scattering, then to trigger (with or without time delay) a photoflash unit and camera. The photographs taken in this way differ markedly when poly(ethylene oxide) or algae are added to the water, as shown in Fig. 8. Thus a change in the external appearance of cavitation may be expected when contamination of a water tunnel by high-polymer substances occurs.

CAVITATION EROSION

An early report (Ref. 9) indicated lowered cavitation erosion in both rotating-disk and magnetostrictive types of test apparatus with polymer solutions. However, Milton Plesset of the California



50 ppm poly(ethylene oxide)

Water

FIG. 7. Appearance of Fully Developed Cavitation on Body of Revolution in Water and in 50-ppm Poly(ethylene oxide) Solution.

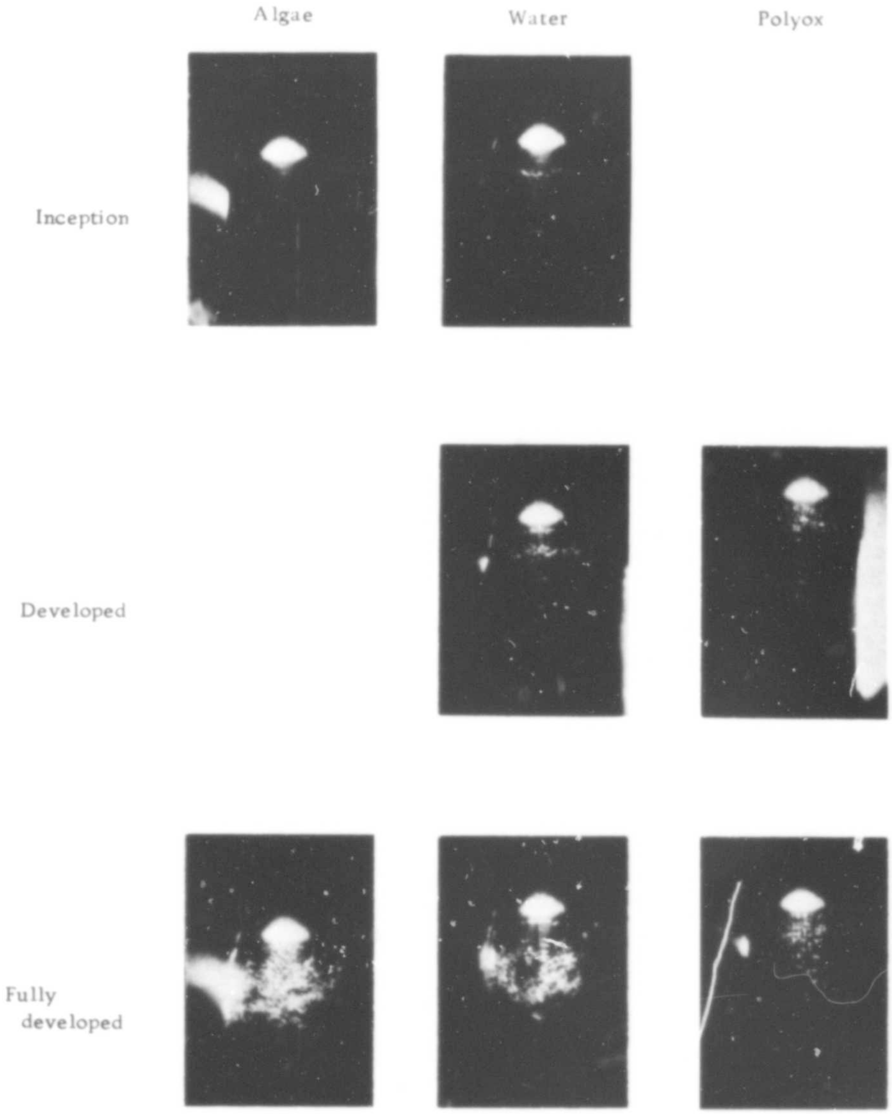


FIG. 8. Appearance of Cavitation on Hemisphere-Nosed Body in Water, Algae, and Poly(ethylene oxide) Solution.

Institute of Technology has been unable to confirm these findings, at least with a magnetostrictive device and ir the polymer solution concentrations that are of the most interest in friction reduction. Using a standardized technique with dished aluminum samples at a vibration rate of 14 kHz (Ref. 10), Dr. Plesset and R. E. Devine, of the Department of Engineering, Cal Tech, obtained the data shown in Fig. 9 for solutions of guar gum, poly(ethylene oxide), and a friction-reducing algae suspension. In this method of testing, at least, there seems to be little change in erosion damage with the polymers present. However, the magnetostrictive technique is not necessarily representative of cavitation erosion in flow situations, and further study is needed to determine whether, in fact, erosion is affected by the use of polymers in a flowing stream.

OTHER MANIFESTATIONS OF ALGAL ACTIVITY IN THE OCEAN

Since the high polymers released by microscopic and large algae are both turbulence-suppressing and surface-tension lowering, it is not surprising that, where large quantities of algae are present, the surface appearance of the ocean is changed. Slicks have been reported from "blooms" or dense concentrations of microscopic algae of several kinds (Ref. 11).

It is further apparent that slicks often accompany the presence of larger algae (Fig. 5), and it has been established (Ref. 12) that the surface tension in these patches of water is greatly reduced. It has also been demonstrated (Ref. 13) that the algae of rocky shores liberate surface-tension reducing materials and are responsible for the increased appearance of foam on the water in such areas.

Color changes of all kinds are further indications of the presence of algal activity. Patches of colored water have been noticed in the ocean since earliest times; these patches may be of almost any color: e.g., white, grey, brown, yellow, or red.

How is the naval architect to be assured that his ship trials are not affected by biological activity in the ocean? The only real answer is to test the water. Portable turbulent-flow friction-measuring devices can be constructed for use on shipboard. One such unit is the turbulent-flow rheometer shown in Fig. 10 and 11. The results shown in Fig. 1 and 2 were obtained on an instrument of this type, with distilled water used as the reference standard.

For the towing tank or water tunnel, a larger, more robust and reliable rheometer of the same general type has been developed and used as a standard for evaluating samples of water and candidate friction-reducing polymer solutions (Ref. 14). The data shown in Fig. 4 were taken with such a device.

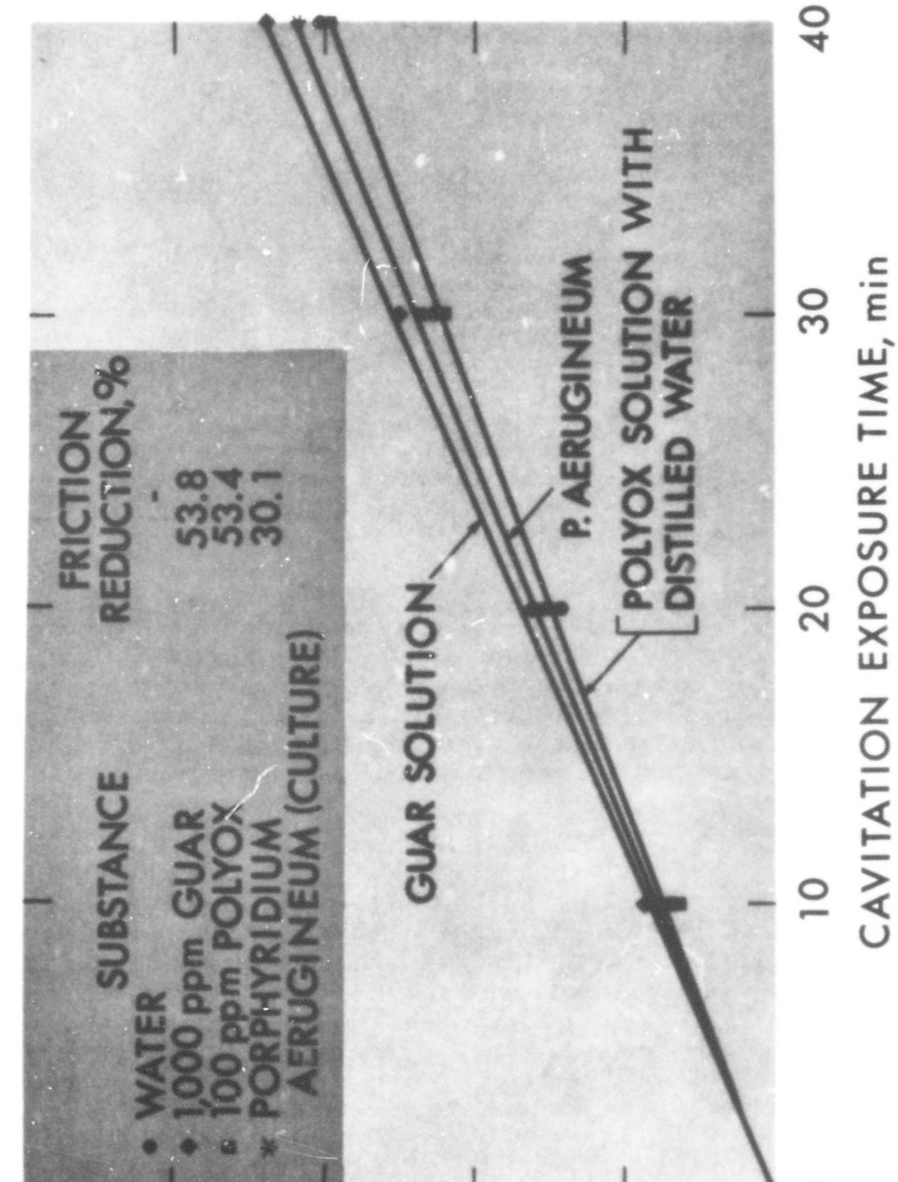


FIG. 9. Cavitation Erosion Data Using Magnetostrictive Technique.

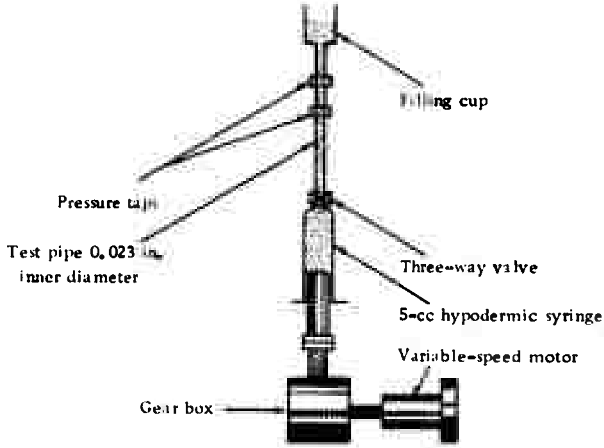


FIG. 10. Schematic of Friction-Testing Apparatus (Turbulent-Flow Rheometer).

Since there is, as yet, an uncertain translation of a friction coefficient in a pipe at one Reynolds number to a flat-plate coefficient at another, departures from the pure-water values obtained with these instruments should probably be used as warnings in the ship-trial, towing-tank, and water-tunnel cases, rather than a basis for attempting quantitative corrections to the resistance under measurement.

CONCLUSIONS

Experiments with algae that secrete high-polymer substances indicate clearly that the influence of these natural products in the oceans and in shore-based hydrodynamic facilities should be considered in measurements involving resistance and cavitation. In these experiments, friction reductions of up to 65% were produced in the laboratory with various types of fresh-water and marine algae. Further study of the occurrence and role of these large organic molecules in natural and manmade bodies of water should be undertaken.

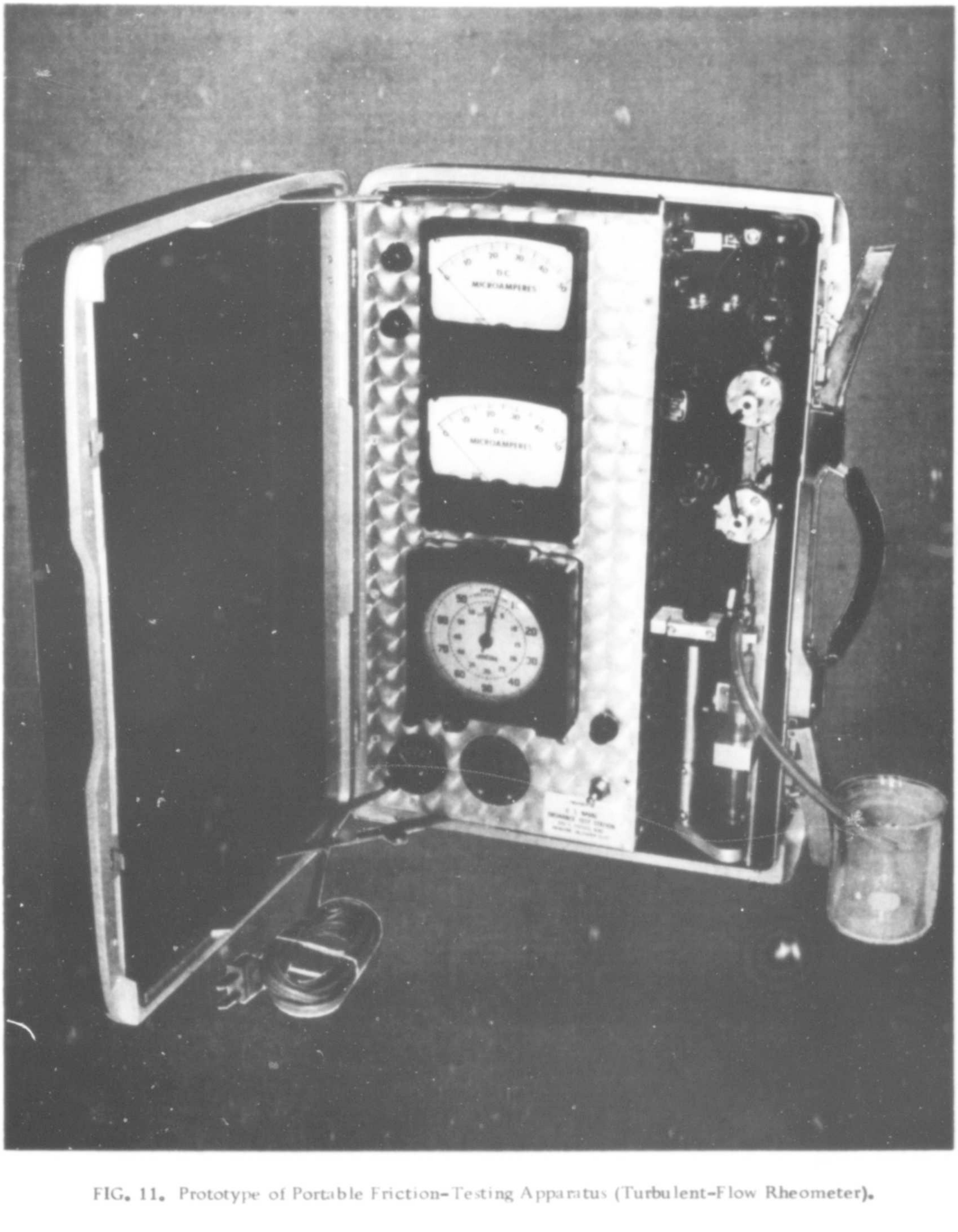


FIG. 11. Prototype of Portable Friction-Testing Apparatus (Turbulent-Flow Rheometer).

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